

*Reprinted from Cold Regions Engineering
Proceedings of the Conference
American Society of Civil Engineers
Held August 16-19, 1999, Lincoln, New Hampshire*

Ice Storms, Trees and Power Lines

Kathleen F. Jones¹

Abstract

Ice storms can cause prolonged outages in the supply of electric power to residents and industry. As we have become more dependent on electric power for lighting, heat, water, and communications, disruptions in the power supply have more severe consequences. This paper reviews a simple ice accretion model for forecasting ice loads in freezing-rain storms. Then, starting from information on the distribution of branch and twig diameters, the relative weights of ice on trees and on wires are compared. Finally, the areas of severe ice storms that have occurred in the southeastern United States are used to show the frequency of ice storms of large and small extents in that region. Utilities can use this kind of information to evaluate their ability to respond to damaging ice storms.

Introduction

Freezing-rain storms often cause disruptions to the supply of electricity. Heat, lighting, food storage and preparation, municipal and private water supply systems, radio, television, cellular phone and computer systems, and agricultural operations all rely on electric power. While some businesses, public facilities and houses have back-up generators that can be brought on line when power is out, generators are not recommended for general use, because of generator maintenance problems, safety concerns, and problems in obtaining fuel when road conditions are bad. Prolonged electrical outages can occur even in ice storms that produce relatively small ice thickness on conductors and wires. Outages can occur when faulty components fail, switches freeze, high winds put additional longitudinal or transverse loads on the line, galloping causes clashing wires and flashovers, or ice-laden trees and branches near the right-of-way fall on the wires. Because of the prevalence of damage from ice-covered trees and wires to distribution lines and low-voltage transmission lines in narrow right-of-ways, this paper will examine the relative ice loads on trees and wires and the typical extents of freezing-rain storms.

¹Research Physical Scientist, Snow and Ice Division, Cold Regions Research and Engineering Laboratory, Hanover, NH 03755, kjones@crrel.usace.army.mil

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 1999		2. REPORT TYPE		3. DATES COVERED 00-00-1999 to 00-00-1999	
4. TITLE AND SUBTITLE Ice Storms, Trees and Power Lines				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Research Physical Scientis, Snow and Ice Division,,Cold Rgions Research and Engineering Laboratory,,Hanover,,NH,03755				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Reprinted from Cold Regions Engineering Proceedings of the Conference American Society of Civil Engineers Held August 16-19, 1999, Lincoln, New Hampshire					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 11	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Simple ice accretion model

The simple ice accretion model for horizontal circular cylinders (Jones 1998) determines the uniform radial ice thickness using simple physics. The standard hourly version of the model was used in mapping extreme ice loads for the United States for the 1998 revision of the ASCE 7 Standard *Minimum Design Loads for Buildings and Other Structures* (ASCE, in press). The back-of-the-envelope version of this model is

$$t = 0.35P \left[1 + \left(\frac{V}{5} \right)^2 \right]^{1/2}, \quad (1)$$

where

t (mm) is the uniform radial ice thickness

P (mm) is the total amount of freezing rain

V (m/s) is the average wind speed during the freezing rain storm.

The term in square brackets gives the relative contributions to the ice thickness from the vertical flux of water from the falling rain and the horizontal flux of water from the wind-blown rain. Note that the uniform ice thickness does not depend on the cylinder diameter. In this formulation of the simple model the horizontal flux term has been linearized and the values of the constants have been combined.

A number of assumptions are made in the simple model. First, it is assumed that the collision efficiency of the rain drops with the cylinder is 1. The collision efficiency of cloud droplets is a balance between the drag on the droplet exerted by the wind as it goes around objects and the inertia of the droplet that tends to maintain a straight-line trajectory. Collision efficiency depends on droplet diameter, wind speed and the diameter of the cylinder (e.g. Finstad 1988). However, the relatively massive rain and drizzle drops travel in virtually straight-line trajectories even in low winds. The second, often conservative, assumption is that all the drops of freezing rain impinging on the cylinder freeze. Detailed ice accretion models typically include a heat-balance calculation, based on numerous assumptions and empirical observations and requiring air temperature and dew point data, to determine the fraction of the impinging precipitation that freezes. Whether or not the drops of freezing rain are supercooled has little effect on the rate of freezing or the freezing fraction, as can be shown by the following calculations: 334 J of heat must be removed to freeze 1 g of water at 0°C. If the raindrops are supercooled, warming 1 g of raindrops to 0°C extracts only 4.2 J of heat for each degree of supercooling. Raindrops supercooled to -5°C, for example, would extract only 6% of the heat that must be removed to freeze that amount of water. Convective and evaporative cooling from wind blowing by the cylinder are the most efficient mechanisms for freezing the impinging water. Third, we assume that the ice accretes uniformly around the circumference of the cylinder. This assumption is a simplification and may or may not be conservative. Ice accreted from freezing rain may form a thin crescent or a bulbous mass on one side of the cylinder, or a layer of ice covering the cylinder with many icicles underneath. Only occasionally is the accreted ice uniformly thick around a wire

or branch. However, assuming a uniform radial accretion is consistent with the level of detail in this simple model. The final, often conservative, assumption is that the cylinder is perpendicular to the wind direction. On cylinders with axes parallel to the wind there will be no flux of water from the wind-blown rain so the second term in square brackets in (1) is zero.

Two empirical observations are used in the simple model. First, the density of the ice formed from freezing rain is taken as 900 kg/m^3 . This value is based on the clear ice accretions that are typically observed and is less than the density of pure bubble-free ice (917 kg/m^3). The second observation relates the liquid water content W in rain to the precipitation rate p in mm/h. The simple model uses Best's formula $W(\text{g/m}^3) = 0.067p^{0.864}$ (Best 1949).

Using (1), uniform ice thicknesses can be determined for any combination of precipitation amount and wind speed to estimate, for example, the potential severity of a forecast ice storm. For $P = 20 \text{ mm}$ and $V = 5 \text{ m/s}$, the uniform ice thickness is 10 mm . For the same amount of precipitation but much higher winds, say 15 m/s , $t = 22 \text{ mm}$, pointing out the significant effect of wind on the accreted ice thickness. A plot of t versus P and V is included in Jones (1998). The uniform ice thickness describes the mass of accreted ice on a wire of diameter d and length L , using any consistent set of units:

$$m = \rho_i \pi (t^2 + dt) L \quad (2)$$

where ρ_i is the ice density. On 100-m-long cylinders with diameters of 10 and 25 mm, for example, a 10-mm uniform ice thickness results in 56-kg and 99-kg loads, respectively.

Ice loads on trees

Tree trimming cycles range from 2 years (Potomac Electric Power Company, Wilson 1999) to 5 years (Granite State Electric, Richard Holmes, personal communication) to 7 years (Bangor Hydro, Ken Miller, personal communication). Trees along scenic roads are typically trimmed more lightly but more frequently. The National Electric Safety Code (NESC) requires that trees that may interfere with ungrounded supply conductors be removed or trimmed, with the extent of trimming required being determined by normal tree growth and the movement of trees and conductors under adverse weather conditions. Some utilities also have programs to identify and remove trees and branches that are likely to damage the lines in wind or ice storms. The amount of trimming that is done is a balance between the utilities' requirements and municipalities' and residents' desires for tree-lined streets or to maintain the rural character of a community. In many ice storms, damage to the distribution and low-voltage transmission line systems occurs when ice-covered branches or entire trees lean on the wires or break and fall on the wires. That static load may be much greater than the weight of ice on the wires. For



Figure 1. Damage to distribution line initiated by ice-covered trees in Malone, New York, in January 1998.

example, in the January 1998 ice storm in the Northeast, ice-laden trees around a farm house in Malone, New York, initiated a cascade failure of the distribution line in both directions from the house, breaking seven poles (Fig. 1). Restoring power to damaged lines is slowed by the need to remove the broken branches and trees before repairs to the wires and poles can be made. Sometimes the damage is so widespread that National Guard and Reserve units are called in to help with tree clearing and removal.

For lines that are vulnerable to tree damage, it is useful to determine the potential load of broken ice-covered trees on the wires, to compare to the corresponding ice load on the wires themselves. To estimate a tree ice load using (2) we need to know the diameters and lengths of the tree's branches and twigs. We determined $L(d)$ for a convenient, recently expired tree across the street from the Cold Regions Research and Engineering Laboratory (CRREL). The 8.5-m-tall ash had been planted in 1986 in a small grassy island between a parking lot and the road, next to distribution lines. The 3-m-tall trunk was 0.28 m in diameter at mid-height. The tree was cut at ground level and dismantled into single twig and branch components (Fig. 2). The length and average diameter of each component were measured. The many small twigs of each main branch were sorted into groups of similar lengths and diameters, and the average length, average diameter, and number of twigs were recorded. The measurements were compiled by diameter and are plotted in Fig. 3, excluding only the trunk of the tree.

As the ultimate goal was to determine the potential ice loads on trees from freezing-rain storms, we wanted an analytic relationship for $L(d)$. We found that the relationship



Figure 2. Dismantled sample tree.

$$L(x < d) = L_T \exp[-(d_0/d)^2] \quad (3)$$

fit the data very well, with the total branch length $L_T = 1538$ m and characteristic diameter $d_0 = 4.1$ mm for this small ash (Fig. 4). The total ice load M on the tree can now be determined from (2), written as an incremental mass dm using the derivative of (3) for dL :

$$M(t) = \int_{d_{\min}}^{d_{\max}} \rho_i \pi (t^2 + xt) L_T \left(\frac{-2d_0^2}{x^3} \right) \exp \left(-\frac{d_0^2}{x^2} \right) dx = \rho_i L_T \pi (t^2 + d_0 \sqrt{\pi t}), \quad (4)$$

where the minimum and maximum branch diameters, d_{\min} and d_{\max} , have been set to 0 and ∞ without loss of accuracy. For ice thicknesses much greater than d_0 , (4) shows that the ice mass on the tree is proportional to t^2 , and for ice thicknesses much less than d_0 , the ice mass is proportional to t . The relationship between ice load and uniform ice thickness for this tree is shown in Fig. 5. Note that (4) has the same form as (2), with the total branch length L_T replacing the wire length L and $\sqrt{\pi}d_0$ replacing the wire diameter d . Relatively small uniform radial ice thicknesses of 5 and 10 mm result in ice loads of 266 and 750 kg, respectively, on this tree. The corresponding ice loads on 10-mm-diameter wires, for a 60-m span side tap of a distribution line for example, are 13 and 34 kg, respectively, with a bare wire weight of 10 kg. On the 20-mm diameter wires of a main line, 5- and 10-mm ice thicknesses produce ice loads of 21 and 51 kg on each 60-m span, with a 40-kg bare wire weight.

Power and phone poles often support many wires for power, telephone and cable

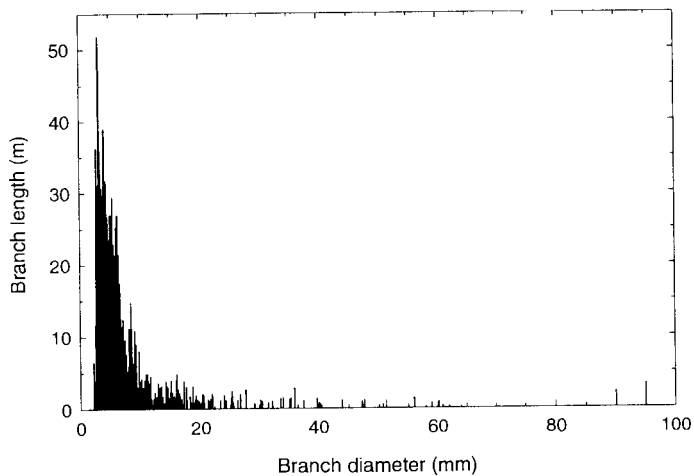


Figure 3. Variation of total branch length with branch diameter for the sample tree.

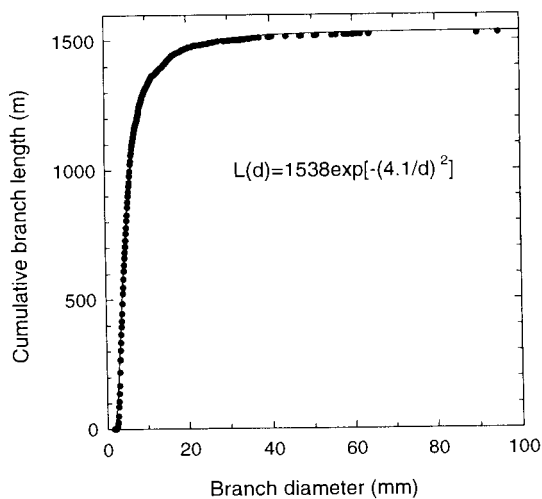


Figure 4. Cumulative branch length data and best-fit curve for the sample tree.

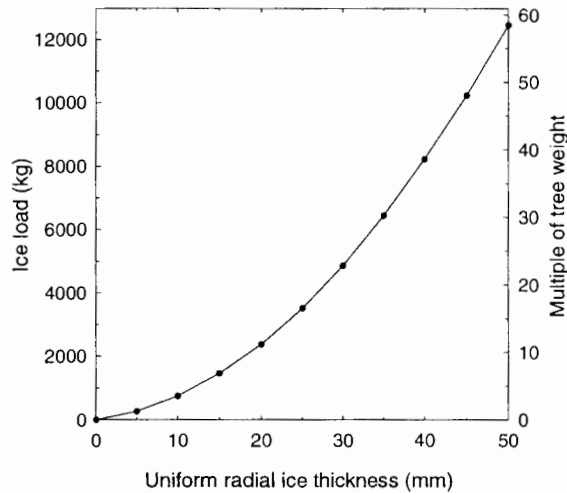


Figure 5. Dependence of ice load on uniform ice thickness for the sample tree.

television, all of which will be covered by ice in a freezing rain storm. The ratio f of the ice load from a single small tree falling on a span of length L to the total wire ice load for N wires with diameter d_i is

$$f = \frac{L_T(t^2 + d_0\sqrt{\pi}t)}{\sum_{i=1}^N L(t^2 + d_i t)} \quad (5)$$

For $d_0\sqrt{\pi} \approx d_i$ for all i , this reduces to

$$f \approx \frac{L_T}{NL} \quad (6)$$

with no dependence on ice thickness. For this particular tree and wire span, with $L_T = 1538$ m and $L = 60$ m, there would have to be 25 wires for the wire ice load to be as large as the tree ice load. In a residential or wooded rural area, there may be many trees per span, all of which increase the potential of damage to the wires and poles.

The tree parameters L_T and d_0 will vary with the tree species, age, size, exposure to the sun and proximity to other trees. Damage to wires and poles may be from many broken ice-covered branches rather than from a single tree and may be exacerbated by the dynamic load of the branch impacting the wire. The failure of a particular tree also depends on the strength and brittleness of the wood, whether the branching pattern is decurrent (broad crown) or excurrent (conical crown), the presence of included (in-

grown) bark in branch junctures, the balance of the crown, and previous damage from human activities, disease, insects and prior ice, snow and wind storms (Hauer et al. 1994). The calculations above serve to illustrate the importance of tree ice loads in assessing the hazard to the distribution system posed by trees near the right-of-way.

Ice storm extent

Broken ice covered trees and branches can damage hundreds of miles of distribution lines and transmission lines in narrow right-of ways during freezing-rain storms. Utilities often request help in restoring power after an ice storm from neighboring utilities. However, if the storm is extensive enough that lines across the service areas of a number of utilities are damaged, the readily available line crews may be stretched thin. Crews must then be requested from farther away, slowing down restoration efforts. In this section, typical ice storm extents are examined.

As part of a project for the Electrical Power Research Institute (Jones et al. 1997) we determined the areas of severe ice storms that occurred between 1949 and 1995 in a portion of the southeastern United States. The study region covered Tennessee, Kentucky, eastern Arkansas and Missouri, northeast Louisiana, northern Mississippi, Alabama and Georgia and western South Carolina, North Carolina, Virginia and West Virginia. Severe ice storms, those with modeled ice thicknesses of at least 13 mm at one or more weather stations are listed chronologically in this 46- year-period in Table 1. The areas in this table were determined for the region of each storm in which ice loads were sufficiently high to damage trees and power lines. This damage information was compiled from *Storm Data*, contemporaneous newspaper accounts, journal articles and Tennessee Valley Authority (TVA) reports. Within these regions the severity of power line damage varied with the distribution of both the population and trees, the icing severity, and the wind speed while ice remained on trees and wires. Some of these storms extended into neighboring states outside the study region.

The areas of these 47 storms range from 9,600 to 450,000 km² (Fig. 6). The 10th percentile storm area is 21,000 km², about the size of Massachusetts. This fifth smallest storm in late February 1962 caused electric and telephone outages in the northern Bluegrass region of Kentucky and in southwestern Ohio lasting up to three days. Storm cleanup was made difficult by heavy rain following the ice storm (NOAA 1962). The median storm footprint area of 45,000 km² would cover Vermont and New Hampshire. This middle-sized storm hit northeastern Louisiana and central Mississippi in early February 1989. Power outages in Louisiana lasted up to 36 hours, and power line repairs in Mississippi took a week (NOAA 1989). The area of the 90th percentile storm is 120,000 km², equivalent to the area of New York or Mississippi. This sixth largest storm in early March 1960 (NOAA 1960, TVA 1960) covered a region in eastern Arkansas and northeastern Louisiana as well as a larger region in central and eastern Tennessee, northeastern Alabama, the northern half of Georgia and into northern South Carolina. In Arkansas and Louisiana the storm was very destructive to shade trees, timber, power lines and telephone lines. In Georgia many communities were isolated when telephone and power lines went down, with outages lasting up to five days. In Alabama the ice storm, de-

Table 1. Severe ice storms in the Southeast (1949-1995).

Dates	Affected states	Area (km ²)
1/30-2/1/49	NC, SC, GA	45,300
1/6-7/50	AR, TN, KY	96,300
1/30-2/1/50	AR, MO, KY, TN, IL, IN	91,400
12/28-29/50	GA, SC	46,100
1/28-2/4/51	LA, AR, MS, TN, KY, IN, OH	260,000
12/20-21/51	GA, NC, SC	49,700
3/1-5/53	IN, KY	10,100
3/2-7/60	GA, SC, AL, TN, LA, AR, MS	120,000
1/26-29/61	GA, AL	43,800
2/23-25/62	KY, OH	21,000
12/24-26/62	GA, TN, NC	34,500
12/22-26/63	MS, LA	21,000
12/31/63-1/2/64	GA, SC	59,000
1/10-18/68	NC, AR, MO, TN, KY	80,800
1/20-21/69	WV, VA	35,500
2/16-17/69	SC, NC, AL, GA	61,600
12/25/69	NC, SC, VA	37,600
2/14-16/70	KY	24,100
2/3-5/71	SC, NC	32,400
11/24-26/71	GA, SC, NC	33,700
1/7-13/73	GA, SC, AR, LA, MS	76,900
12/30/73-1/6/74	LA, AR, MS, TN, KY	131,000
2/4-5/75	SC, NC	38,800
1/11-24/78	SC, NC, VA	32,900
12/8-12/78	AR, TN, MO, IL, IN	106,000
12/30/78-1/16/79	AR, MS, TN, KY	131,000
1/19-23/79	VA, NC	39,400
2/6-8/79	GA, SC	31,900
2/16-20/79	LA, MS, AL, GA, SC	60,300
2/24-27/79	AR, MO, IL	78,200
12/18-22/81	TN, KY	47,900
12/31/81-1/1/82	GA, SC, NC, WV, VA	44,500
2/26-28/82	AL, GA, SC	40,900
1/20-23/83	MS, AL, TN, GA, NC, SC, KY, IN, OH	450,000
1/31-2/10/85	MS, AL, TN, GA, SC	115,000
2/16-18/87	KY, WV	71,000
2/27-28/87	WV, VA	11,100
1/6-11/88	MS, AL, GA	88,800
2/2-11/89	LA, MS, AL	44,800
3/4-9/89	MO, IL, KY	31,100
12/21-28/90	AR	33,700
2/24-3/2/93	AR, GA, SC	24,300
1/16-22/94	AR, MO, IL, KY, TN, IN	112,000
2/8-14/94	AR, MO, MS, AL, TN, SC, NC, KY, WV, VA	315,000
3/1-4/94	WV, VA, NC	31,300
3/8-10/94	KY, WV	26,700
1/6-7/95	KY	9,600

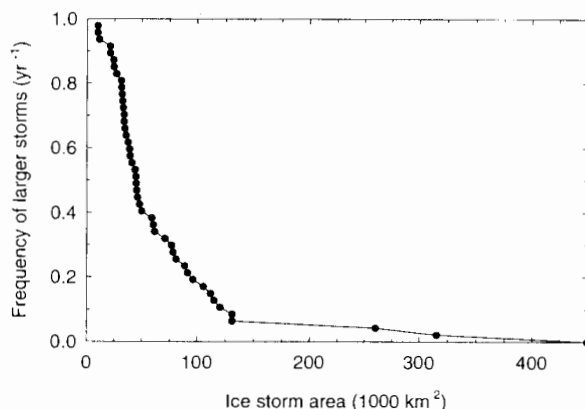


Figure 6. Areas of ice storms in the Southeast, 1949–1995.

scribed as the most severe ice storm in memory, was confined to higher elevations with hundreds of kilometers of telephone and power lines damaged, causing considerable losses in the poultry industry. In Tennessee the combination of heavy ice loads and strong winds damaged trees, power lines and telephone lines from the Cumberland Plateau to the border of North Carolina, primarily at higher elevations. Power and telephone outages lasted over two weeks in some rural areas. The areas of these 10th, 50th and 90th percentile storms will be exceeded on average nine times, five times and once, respectively, in any ten-year period in this 500,000-km² region.

Conclusions

A simple ice accretion model that can be used for estimating ice loads in forecast freezing-rain storms was described. The model shows that the uniform radial ice thickness depends on the amount of freezing rain and the wind speed and does not vary with the diameter of the ice-covered branch or wire. The ice load, however, increases with diameter. From information on the distribution of branch and twig diameters for one tree, a general formulation for branch length distribution that depends on the total branch length and a characteristic branch diameter was obtained. This general formulation was used to determine the total ice load on a tree for any uniform radial ice thickness. The relative weights of ice on trees and on wires of a distribution line were compared, and it was shown that ice-covered trees and branches falling on wires may impose significantly larger loads on the supporting poles than the ice on the wires themselves. Broken ice-covered trees and branches may damage hundreds of kilometers of power lines in a freezing rain storm. The speed with which utilities can restore power after the storm is affected not only by the amount of ice, but also by the extent of the region in which damage to the power distribution system occurs. The severe ice storms that have hit the southeastern United States were used to determine the frequency of ice storms of large

and small extents in that region. Utilities can use ice storm frequency data, along with information on the size of their service area and the total length of their distribution lines and low-voltage transmission lines, to evaluate their ability to respond to damaging ice storms.

Acknowledgments

This research was supported by the AT42 project Extreme Loads from Freezing Rain. Paul Olsen of Dartmouth kindly arranged for the dead tree to be cut down and Keith Ford at Dartmouth Printing provided information about the tree. Richard Holmes of Granite State Electric provided information on typical distribution wire dimensions and span lengths.

References

- ASCE (in press) *Minimum design loads for buildings and other structures*. ASCE7-98, American Society of Civil Engineers, New York.
- Best, A.C. (1949) The size distribution of raindrops, *Q. J. Royal Met. Soc.*, 75, 16-36.
- Finstad, K.F., Lozowski, E.P. and Gates, E.M. (1988) A computational investigation of water droplet trajectories, *J. of Atmos. and Oceanic Technology*, 5, 160-170.
- Hauer, R.J., Hruska, M.C. and Dawson, J.O. (1994) Trees and ice storms: The development of ice-storm resistant urban tree populations. Special Publication 94-1, Department of Forestry, U. of Illinois at Urbana-Champaign, Illinois, 12 pages.
- Jones, K.F. (1998) A simple model for freezing rain ice loads. *Atmospheric Research* 46, 87-97.
- Jones, K.F., Mulherin, N.M. and Ryerson, C.R. (1997) EPRI freezing rain ice mapping project: Region 2. CR-00020, Project 3748-09, Electrical Power Research Institute, Haslet, Texas.
- NOAA (1959-1995) *Storm Data*. National Climate Data Center, Asheville, North Carolina.
- TVA (1960) Snow and ice storms of 1959-1960 in Tennessee River Basin. Tennessee Valley Authority, Chattanooga, Tennessee, 71 pages.
- Wilson, S. (1999) Officials look for lessons in Pepco's darkest days. *Washington Post*, January 31, 1999, p A16, Washington, D.C.